Selective Processing of Aluminum Sheet

Project ID: MAT232

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Argonne National Laboratory

2021 DOE Vehicle Technologies Office Annual Merit Review
June 24, 2021

BATTELLE

LMCP OVERVIEW

LMCP overview

Timeline

- Lab Call Award – September 2020
- Kickoff – November 2020
- End – September 2023
- 5% Percent complete

Budget

- Total project funding $15M/3 years
- Funding for FY 2021 - $5M

Lightweight Metals Core Program Overview

	Title	# of Projects	FY21
Thrust 1	Selective Processing of Aluminum Sheet Materials	3	$1,300,000
Thrust 2	Selective Processing of Aluminum Castings	3	$1,450,000
Thrust 3	Selective Processing of Magnesium Castings	2	$1,100,000
Thrust 4	Crosscutting Thrust - Characterization, Modeling and Lifecycle	7	$1,150,000

Barriers and Technical Targets

- **Materials Performance and Cost** limit the penetration of lightweight Al and Mg alloys into the entire range of vehicle
- **New Alloy** development is slow and costly
- **Recyclability** is complex due to large number of different alloys

Partners

- Program Lead
  - Pacific Northwest National Laboratory
- Partner Laboratories
  - Oak Ridge National Laboratory
  - Argonne National Laboratory
- Industry Engagement
  - Informal support and guidance from OEMS and Tier 1 suppliers
  - CRADAs planned for future years

THRUST 1 OVERVIEW

LMCP Thrust 1 Overview

Selective Processing of Aluminum Sheet

Timeline/Budget

- Project start: Oct 2020
- Project end: Sep 2023
- Percent complete: 5%
- Thrust 1 Budget
  - FY21: $1,300k
  - FY22: $1,325k (planned)
  - FY23: 1,300k (planned)

Technical Barriers

- Material specifications are often over-engineered, driven by very localized performance requirement in select regions of a component design.
- Lack of models and design knowledge for heterogeneous structures that enable putting the right properties in the optimum location of a component/assembly.
- Expanding use of different alloys complicates recycling strategies for aluminum and lightweight vehicle structures.

Thrust 1. Selective Processing of Aluminum Sheet

Project	Title	FY21
1A	Sheet Materials with Local Property Variation (PNNL/ANL)	$500k
1B	Form-and-Print – AM for Localized Property Enhancement (ORNL)	$200k
1C1	High-Shear Thermomechanical Processing (PNNL)	$400k
1C2	Localized Thermal-Mechanical Processing (ORNL)	$200k
	Thrust Totals	$1,300k

Partners

- Program Lead Lab
  - Pacific Northwest National Lab (PNNL)
- Thrust 1 Participating Labs
  - Pacific Northwest National Lab (PNNL)
  - Oak Ridge National Laboratory (ORNL)
  - Argonne National Laboratory (ANL)
- Thrust 1 Collaborators
  - Ford Motor Company
  - Computherm
  - Mazak
  - General Motors

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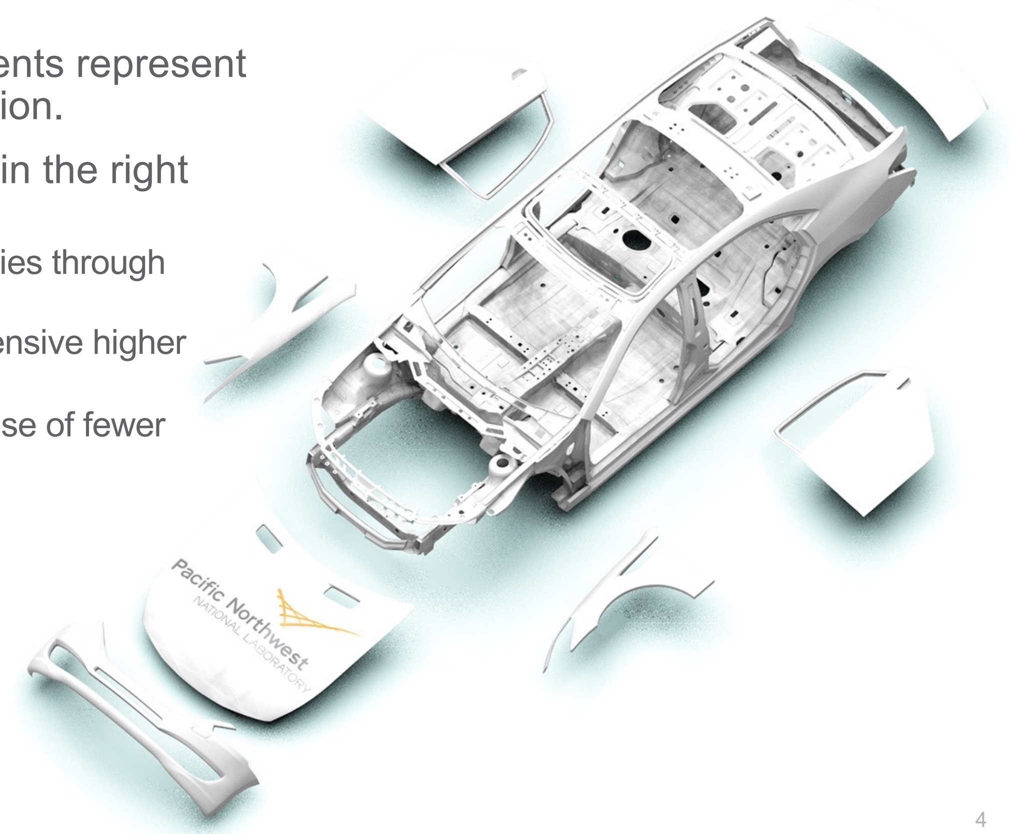
Relevance

Stamped or formed sheet metal components represent largest percentage of the glider construction.

Aluminum sheet with the right properties in the right location offers:

- Opportunity to optimize lightweighting strategies through down-gaging and better geometric effects
- Reduced costs compared to using more expensive higher performing monolithic alloys
- Decreased complexity for recycling through use of fewer alloys



Goal: Demonstrate ability to modify parts at various stages along manufacturing process and illustrate how this would be adopted by industry.

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Approach

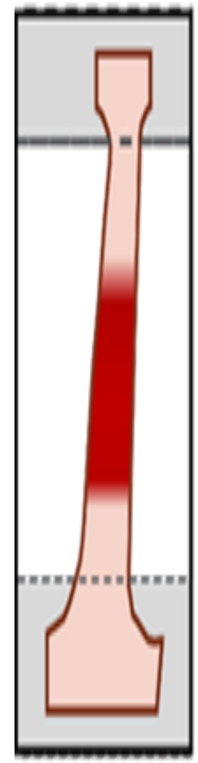
Oak Ridge National Laboratory

Optimize use of common aluminum sheet alloys through heterogeneous processing methods, while increasing ability to recycle for better sustainability

Advanced process technologies categories:

1. Solid-Phase Processing,
2. Additive Manufacturing,
3. High-Intensity Thermomechanical Treatments

Performance requirement metrics driven by stamped and assembled BIW components such as: B-pillars, crash-box, and roof systems.



Increased yield and fracture strength to resist deformation

Increased strength and stiffness for bridging and load transfer to other areas away from occupant

Increased elongation Improved energy absorption

B-Pillar example of tailored and desired properties

THRUST 1 PROJECTS

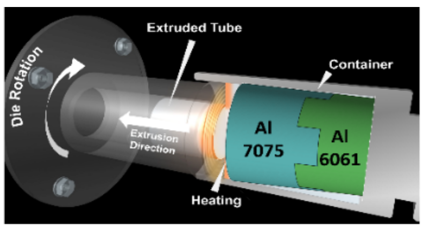
Approach

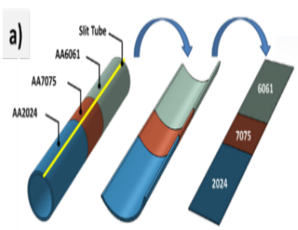
Three projects focused on methodologies to control sheet microstructure in 5000, 6000, 7000 series aluminum to tailor the right property in the right place.

Project 1A

Sheet Materials with Local Property Enhancement

Shear Assisted Processing and Extrusion (ShAPE™)

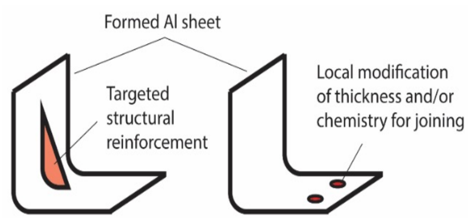




Scott Whalen

Project 1B

Form-and-Print: Additive Manufacturing for Localized Property Enhancement of Al Sheet

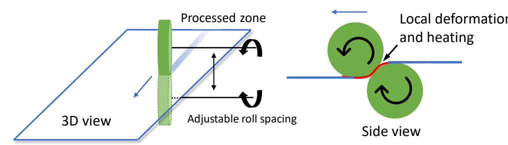


Schematic of Form-and-Print approach for adding structural reinforcement or modifying high-strength Al sheet for joining.

Alex Plotkowski

Project 1C

Local TMP to Address Challenges to Implementing Aluminum Sheet

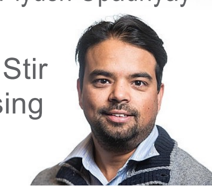


Roller Bend-Unbend Processing

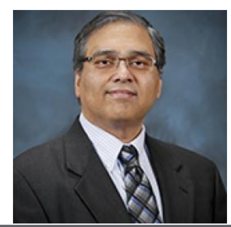
Mert Efe

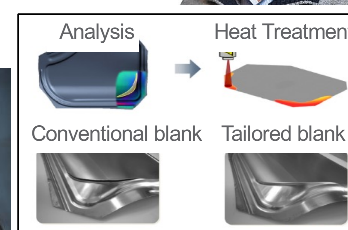
Piyush Upadhyay

Friction Stir Processing



G. Muralitharan





Sonic & Laser Processing

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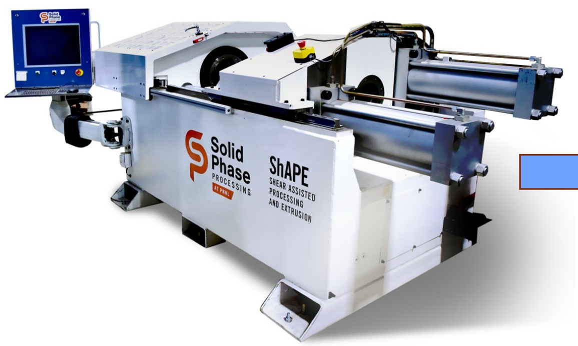
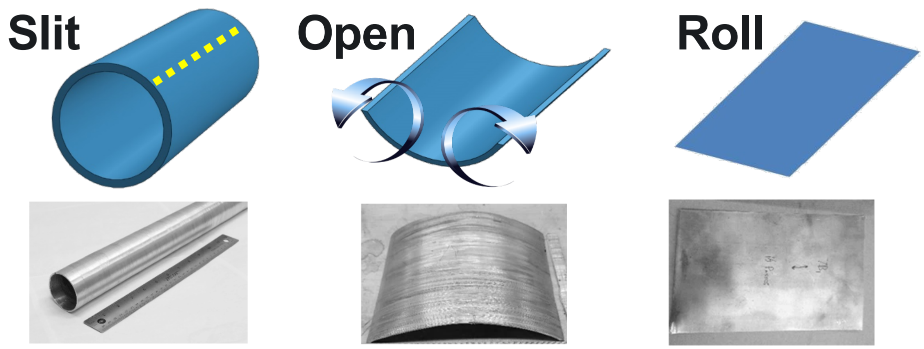
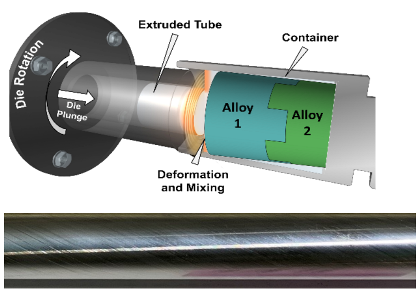
Project 1A: Approach





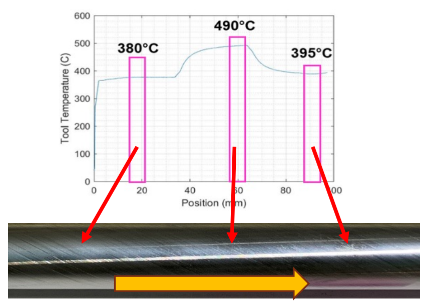
Tasks & Tailored Products

Task 1
Multi Alloy Extrusion



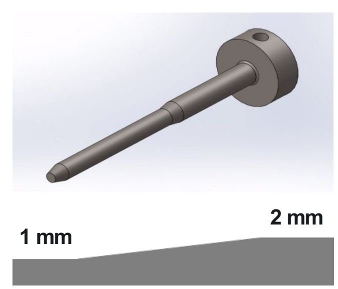
Alloy 1 Transition Alloy 2

Task 2
Variable Properties



Properties vary along length

Task 3
Variable Thickness



Smooth transition

- **Develop techniques on research-scale machine**
- **Scale-up width and process rate in out years**

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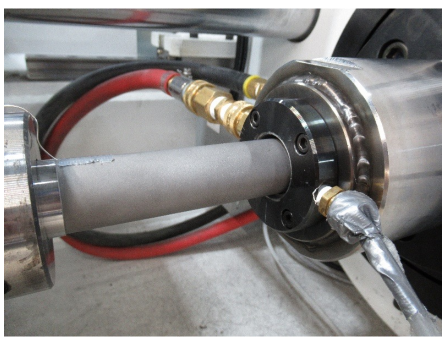
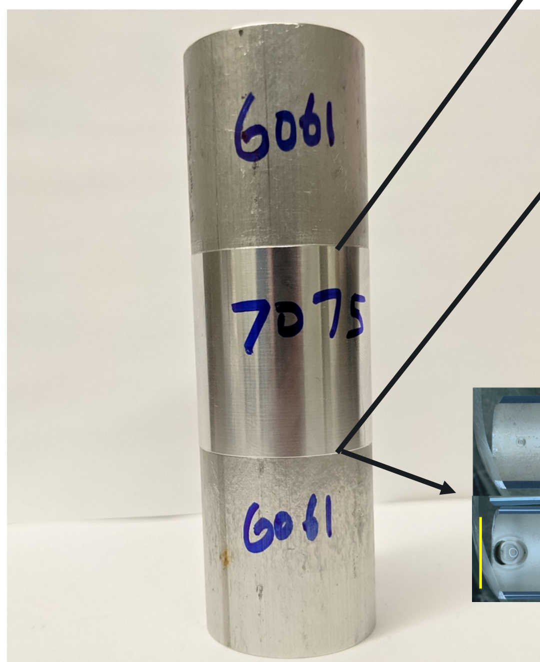
Project 1A: Accomplishments
Task 1: Multi-Alloy Extrusion

Tooling
12 mm OD
10 mm ID

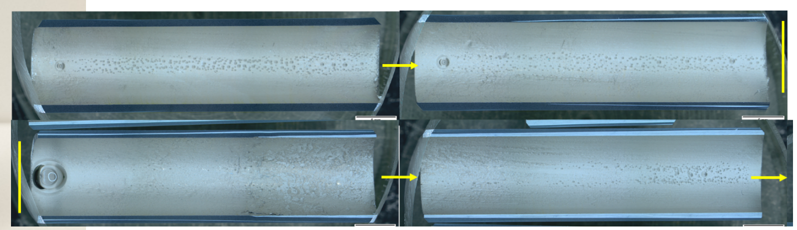


Stack of multi-alloy billets



First Transition

Second Transition



Cross section showing transition from 6061 to 7075 to 6061

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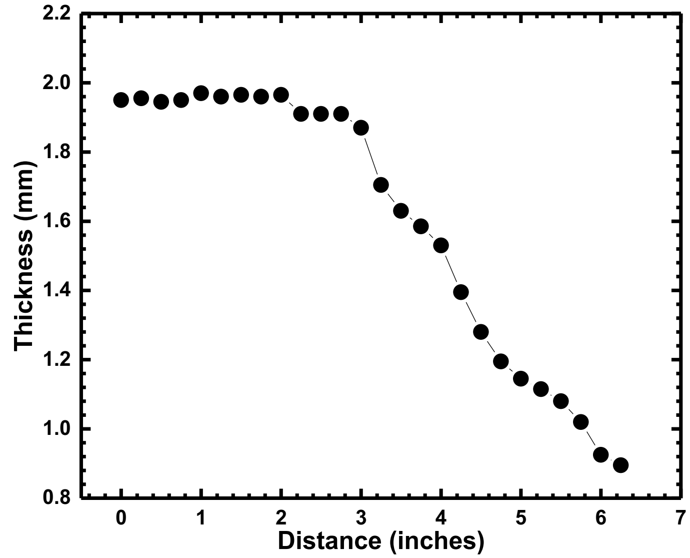
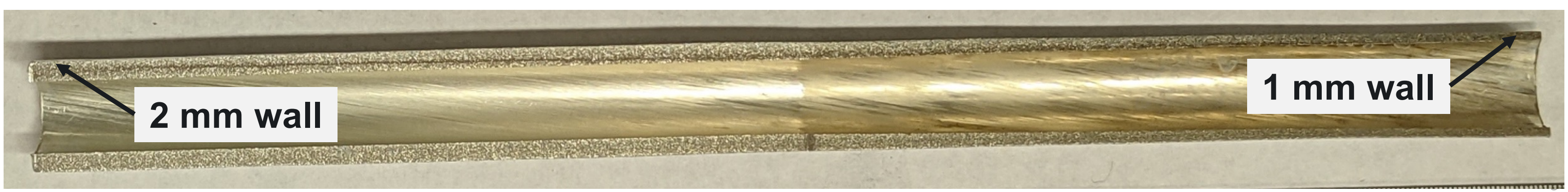
Project 1A: Accomplishments
Task 3: Variable Thickness

Tapered mandrel to transition inner diameter from 8 mm to 10 mm

Wall thickness variation vs. length





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Project 1B: Approach

Alloy Selection → Process Optimization → Materials Characterization → Initial Component Demonstration

Alloy Selection

- Identify relevant sheet alloys for automotive applications
- Consult with OEMs
- Select suitable filler metals

Process Optimization

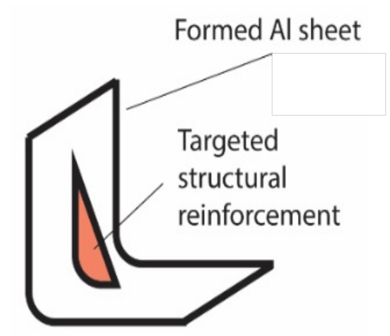
- Utilize process modeling and computational thermodynamics
- Design of experiments

Materials Characterization

- Minimize defects
- Characterize microstructure with respect to process conditions
- Validate computational models

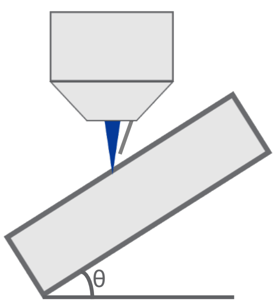
Initial Component Demonstration

- Demonstrate a rib-stiffened formed sheet component



Project 1B: Accomplishments

- Mazak facility preliminary setup, single bead deposits to determine appropriate process parameters
- Machining top surface flat after depositions, depth of beads was approximately 0.5-1.0 mm

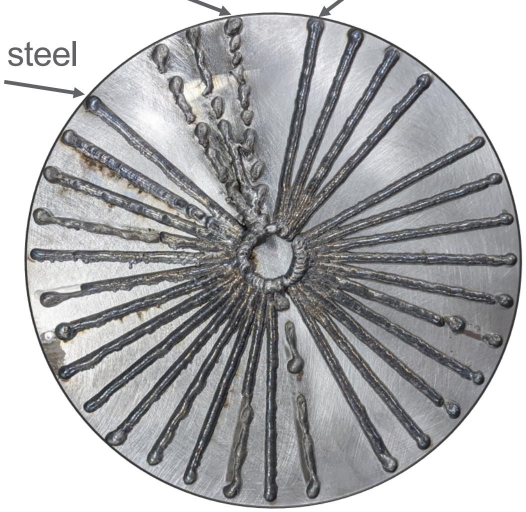


Substrate was tilted at angle to laser to prevent back-reflection

Table 1. Initial parameter set

Parameter	Value
Laser Power	4000 W
Wire Power	104 W
Wire feed rate	88 in/min
Traverse rate	406 mm/min
Gas flow	20 L/min (Argon)
Initial dwell*	5 s with gas only 2 s gas + laser
End dwell*	0.1 s gas + laser

*Initial and end dwells done at the beginning and end of each pass, respectively



Single bead deposits of Al 4043 wire on Al 6061 substrate

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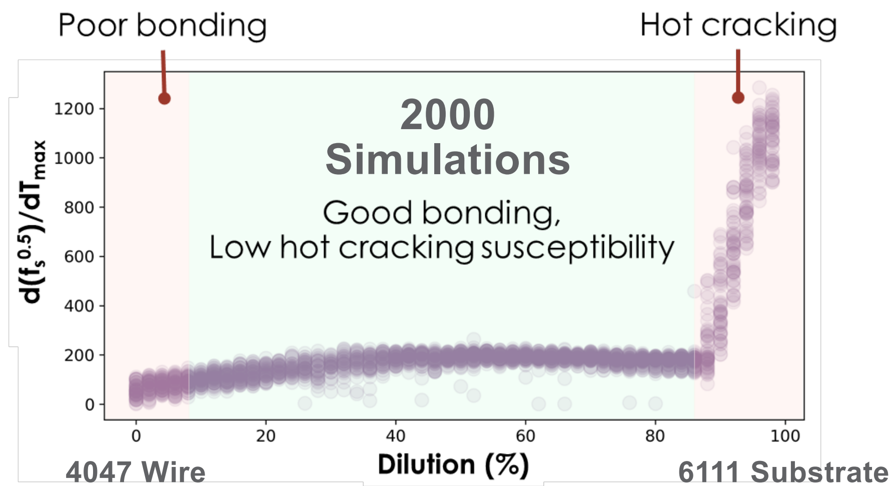
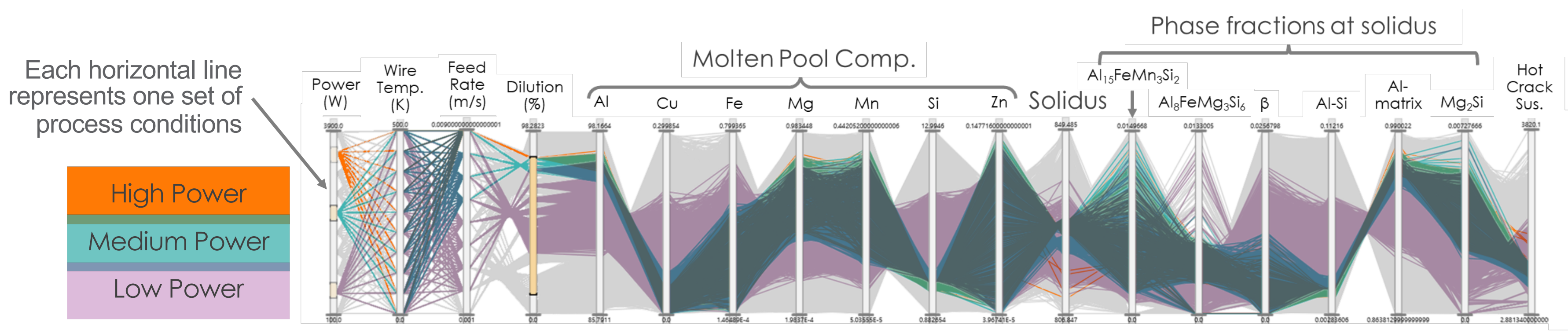
Technical Accomplishments – Computation (Cost share with P2C)

- Preliminary development on high-throughput thermodynamic calculations
- Efficiently compute, analyze, and visualize large data sets
- Example: Computing hot-tear susceptibility as a function of dilution of the filler material
  - Showing 6111 + 4047
  - Visualize large data set using parallel coordinate plots





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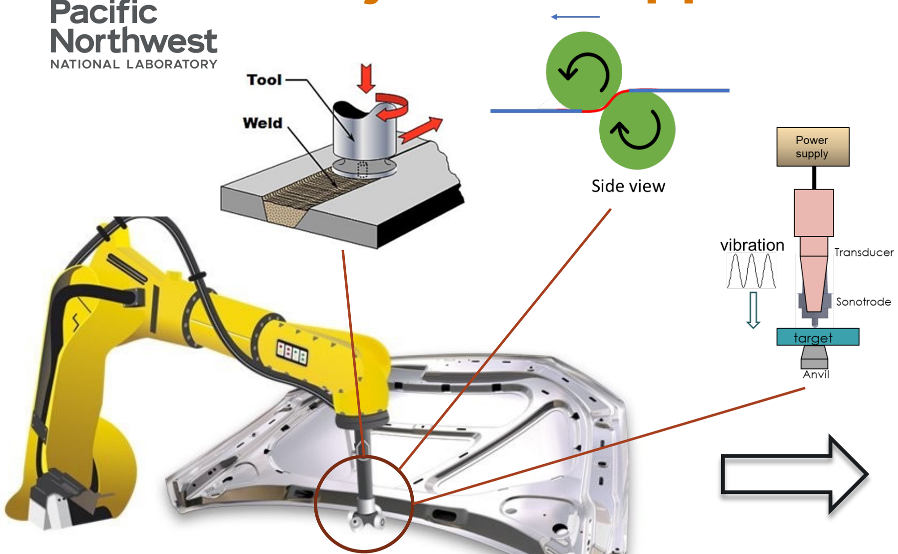
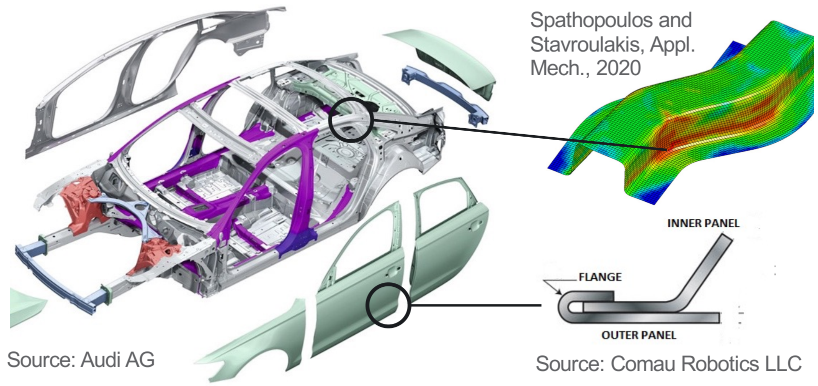
Project 1C: Approach



Source: M. Hosseinjani, Groupe PSA



Source: Audi AG

Spathopoulos and Stavroulakis, Appl. Mech., 2020

Source: Comau Robotics LLC

Enable tight bend radii without cracking or other edge effects

- Increase local formability of components by obtaining dynamically recrystallized, shear textured microstructures by local deformation and heating of age/work hardened sheets
- Retain most of the initial strength without any further heat treatments
- FY21 goal is to demonstrate improvement in radius/thickness ratio by 25%, higher in out years
- At the project end, demonstration of potential manufacturing line integration by apparatus designs for roller bend-unbend and FSP that can be attached as end effector to robots

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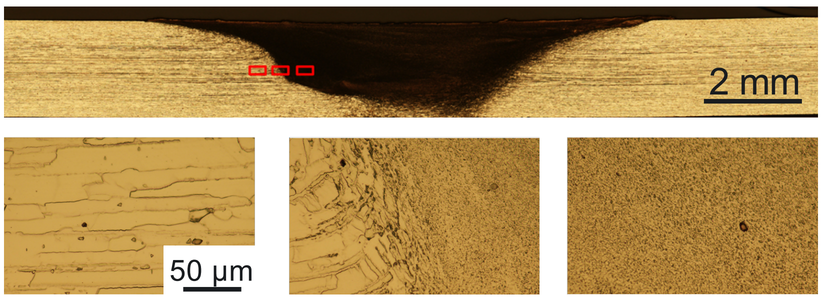
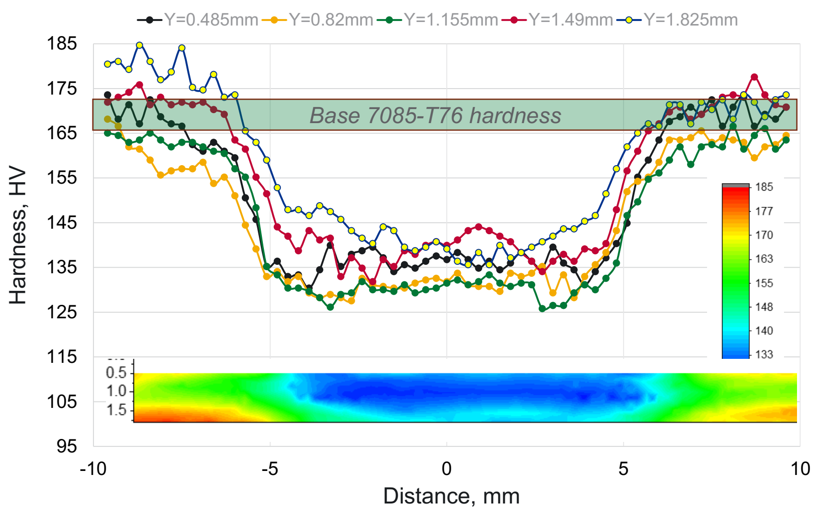
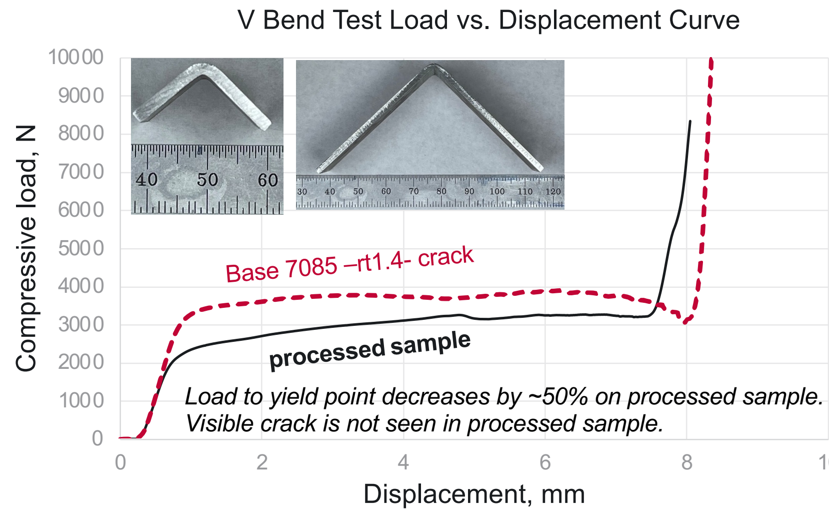
Project 1C: FSP Accomplishments







- Demonstrated FSP of Al7085-T76 sheet at speeds up to 3 m/min (maximum speed of the machine), processing temperatures ranging from 400-480 °C
- Demonstrated ~ 20% softening of processed region in micro hardness measurements
- Successful samples show reduced load to yield point in bend tests with similar radius/thickness ~ 1.5

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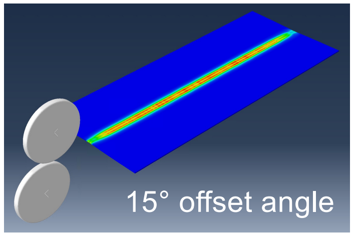
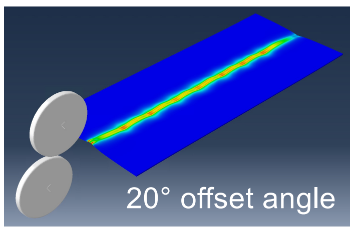
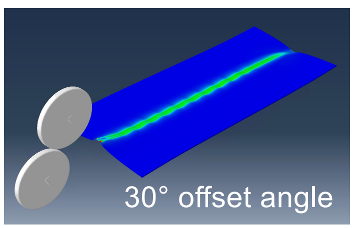
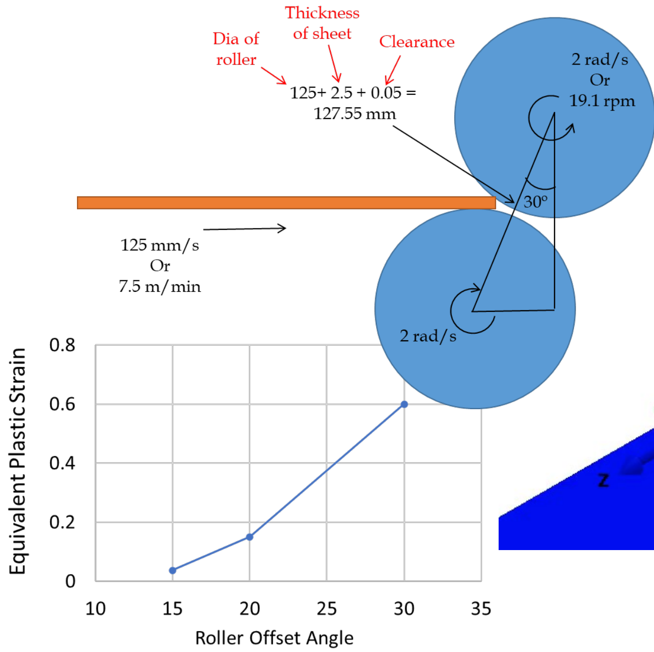
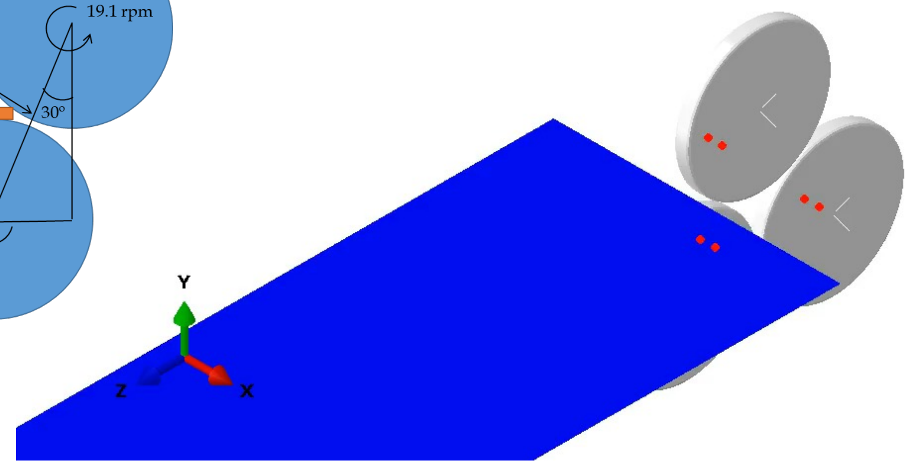
Project 1C: Roller Bending-Unbending Accomplishments











- Completed FE simulations the process by using Al 5182-H32 material properties
- Simulated various boundary conditions, speeds, roller angles, friction coefficients, supports and roller configurations
- Demonstrated $\bar{\varepsilon} \approx 0.6$ in the narrow processed zone, with minimal distortion in the sheet
- Started building the actual setup using commercially available bead rollers

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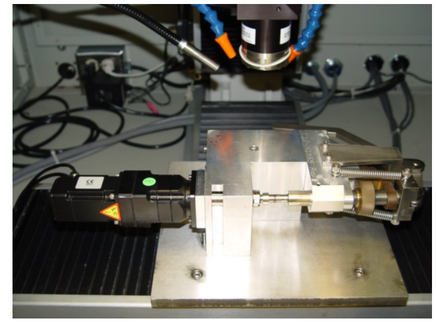
Project 1C: Laser Softening Feasibility Accomplishments

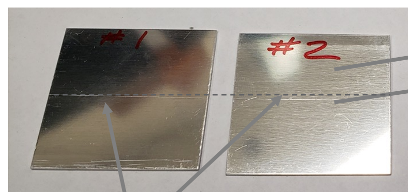
OAK RIDGE
National Laboratory

- Laser system used to perform several local trial heat-treatments
- Wide range of parameters possible
  - Maximum mean power: 350W
  - Maximum pulse energy: 50 J/pulse
  - Maximum peak power: 4.5 kW
  - Pulse Width range: 0.5-50 msec
  - Repetition Rate: 0.2-500 Hz
  - 4 axes CNC control, 3 linear, 1 rotary
  - Working envelope: 12 X 12 X 6 inches
  - Travel Speed: 0-100 IPM
- Local tensile tests show reduction in yield strength by ~ up to 13%
  - Further process development and optimization required

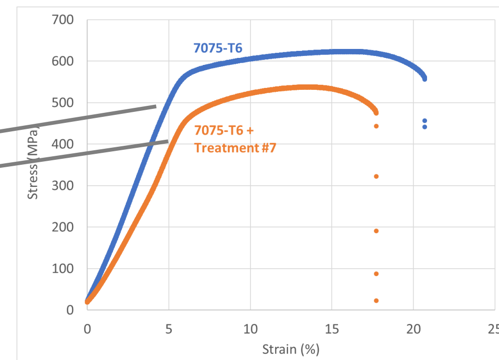
Lumonics 702H/ Pulsed Nd:YAG 1064 nm system with translation stage



Local heat-treated 7075-T6



Line of heat-treatment



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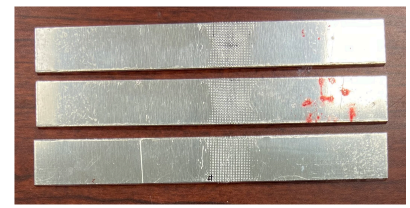
Project 1C: USAM Trials 7075-T6 sheet Accomplishments

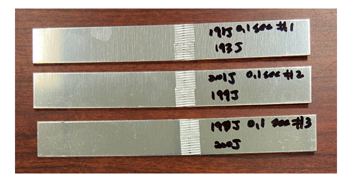
Multiple process variables must be selected

- Single vs dual Sonotrode
- Sonotrode design tip dimension:
  - Rectangular shape vs square shape ($7x7\ mm^2$)
- Ultrasound Parameters
  - Power: 2.5kw
  - Time: 0.5s-4s
  - Pressure: 60psi

USAM setup

Processed Samples





P=2.5KW, p=60psi, t=0.1,0.2,0.3s

Used $7x7\ mm^2$ Sonotrode

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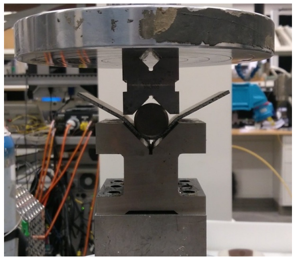
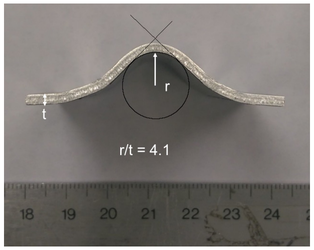
Project 1C Accomplishments: Testing Standard Development

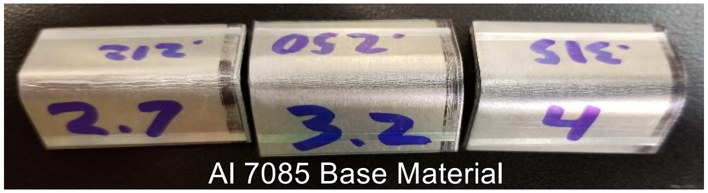
- Collaborative efforts in developing two types of formability test standards

V-Bend Test



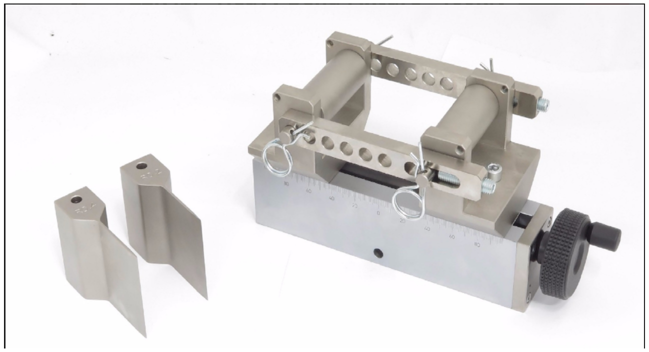


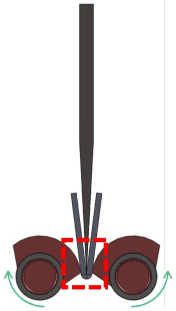
r/t = 1.4 cracked r/t = 1.6 not cracked r/t = 2.0 not cracked



- Developed according to ASTM E290
- Can get minimum bend radius/thickness ratio (r/t) before cracking
- Started testing base materials and processed sheets

VDA 238-100 Test





Noder et al., Exp. Mech., 2020

- German standard
- Will be used with DIC
- Can get maximum bend angle
- Minimum r/t can be measured after the test
- Started design of the fixture

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Pacific Northwest National Laboratory

Oak Ridge National Laboratory

Year 1 Milestones

	Project	Description	Date
✓	1A	Design tooling and billet configurations for variable wall thickness and multi-alloy extrusions	12/31/2020
✓	1A	Fabricate multi-alloy aluminum tubing using ShAPE to join dissimilar aluminum alloys such as 6XXX to 7XXX and/or 5XXX to 6XXX as extruded tubing	3/31/2021
	1A	Fabricate variable wall thickness tubing from 7XXX, 6XXX, or 5XXX.	6/30/2021
	1A	Mechanical property and microstructural characterization of multi-alloy aluminum tubing	9/30/2021
✓	1B	Down-select a specific wrought Al alloy for demonstration with the Form-and-Print approach	3/31/2021
	1B	Demonstrate coupon level AM fabrication of a rib stiffened sheet structure using Form-and-Print	9/30/2021
✓	1C1	Demonstrate softening in age-hardened sheet by friction stir processing	3/31/2021
	1C1	Design of the bending-unbending rolls and the process parameters	6/30/2021
	1C1	Manufacturing and assembly of the components for the bend-unbend process	9/30/2021
✓	1C2	Complete initial trials on local heat-treatments of 7xxx sheet	12/31/2020
✓	1C2	Develop initial process parameters for power ultrasonic edge treatment on trimmed high strength aluminum alloy sheets	3/31/2021
✓	1C2	Evaluate room temperature tensile characteristics of locally heat-treated 7xxx sheet	6/30/2021
	1C2	Demonstrate bend radii below 2x sheet thickness for a 7xxx series Al alloy using at least one processing technique	9/30/2021

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Collaborations and Coordination with Other Institutions

- Core team
  - Shared resources
  - Minimum monthly web-conferences to exchange and discuss data
    - Peer-to-peer conversations & publishing
    - Intra-project coordination and scope alignment
    - Thrust level reviews
  - Co-developing standards & test procedures
  - Leveraging HPC and adv. Characterization capabilities
- Industry and other stakeholder engagement
  - Technical barriers and relevance active advisors: Ford, General Motors and Honda
  - Briefings to USDRIVE Materials Technical Team
  - Planned annual opportunities to disseminate results via conferences and workshops
  - Suppliers providing technical assessments and/or equipment/materials

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Reponses to Previous Year Reviewers' Comments

OAK RIDGE National Laboratory

First year for project execution – no prior year review.

THRUST 1 PROJECTS

Proposed Future Research

Project 1A

Sheet Materials with Local Property Enhancement

Multi-alloy extrusions
- Investigate effect process parameters and billet interface geometry on extent of mixing and joining within transition zones

Variable properties
- Map effect of process temperature and feed rate on properties
- Investigate effect on properties of flatting tubes into small strips

Cast billet processing
- Billets received and prepared
- Initiate AA 6111 and 5182 once process parameters and heat treat response trends established from AA 6061

Project 1B

Form-and-Print: Additive Mfg for Localized Property Enhancement of Al Sheet

Continue with parameter exploration to understand:
- Boundary conditions
- Influence of process conditions and filler chemistry

Demonstrate coupon level AM fabrication of a rib stiffened sheet structure
- Assess effect of structural reinforcement and residual stresses
- Tailor chemistry to control microstructure and properties

Project 1C

Local TMP to Address Challenges to Implementing Aluminum Sheet

Roller Bend-Unbend Processing
- Continue V-bend tests, with procrssed and as-received (benchmark) sheet
- Smaller r/t ratio assessments, r/t < 0.9
- Roller bending trials with 5182

Friction Stir Processing
- FSP with 7075-T6, 5182 and 6111
- Establish optimal process parameter windows per material condition
- Assess transferability to robotic system

Ultrasonic & Laser Processing
- Continue mapping parameter space and assess effects of themal-treatments using sonotrode and laser

LMCP Thrust 1 projects have established multi-year work plans. Scope will be adjusted annually based on stakeholder feedback, discoveries, and down selection of technical approaches.

*Any proposed future work is subject to change based on funding levels

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Summary Slide

OAK RIDGE National Laboratory

- Trial experiments underway across all tasks to illustrate affect of various thermal & thermomechanical processes on local properties.
- Project 1A: Sheet Materials with Local Property Variation (PNNL)
  - High-shear processing conditions of ShAPE™ technology will metallurgically forge alloys together that have significantly different flow stresses
  - Transition from one alloy to the next is not a step function but a gradient
- Project 1C1: High-Shear Thermomechanical Processing (PNNL)
  - Model simulation are providing insight into the proper degree of bend/unbend and tooling design to achieve local plasticity without damage
  - Friction stir processing showed a ~ 20% softening of processed region results in the ability to reduced load to yield with bend tests down to radius/thickness ~1.5
- Project 1C2: Localized Thermal-Mechanical Processing (ORNL)
  - Laser system completed several local trial heat-treatments, with local tensile properties showing reduction in yield strength by up to 13% resulting in improved ductility

The processes pursued as part of Thrust 1 are starting to reveal how aluminum sheet can be locally tailored to put the right properties in optimum locations of a component to maximize lightweighting

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Thank you